Aspects of Next-to-Leading Order QCD at Hadron Colliders

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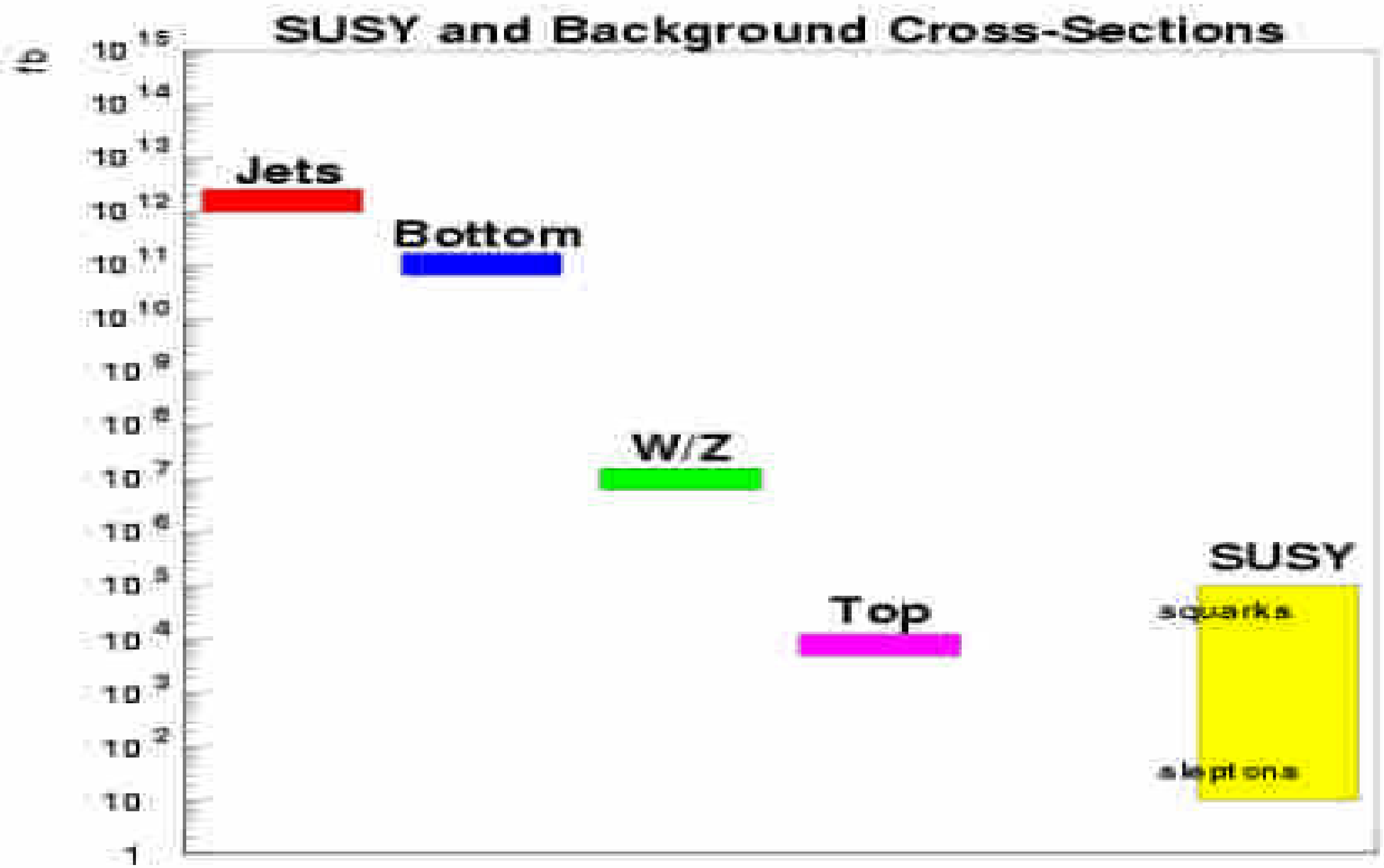
Tree level

- Automatic calculation of most phenomenologically relevant processes via numerical methods, e.g. Madgraph/Helas $\rightarrow$ MadEvent, ALPGEN, CompHEP, Sherpa.
- Easy to interface with a parton shower such as Pythia or Herwig
- Unfortunately, the overall normalization of the cross section can be very uncertain, e.g. $W + 4$ jets is proportional to $\mathcal{O}(\alpha_s^4)$; running α_s so that it changes by 10% leads to a 40% uncertainty in the cross section
- Sometimes the tree level diagrams don't capture enough of the essential physics, e.g. the structure of jets, new partonic processes entering at higher orders
- New analytic results for tree level diagrams ('twistor-inspired', recursion relations) may yield deeper insight into the structure of QCD. So far, simplified results haven't been used to improve our existing tools.

Next-to-leading order

- Less sensitivity to renormalization and factorization scales, so cross sections become more predictive
- Better assessment of backgrounds for new physics searches
- Confidence that cross sections are under control for precision measurements
- More physics begins to be included
- Unfortunately, the interface with a parton shower is much more difficult. Recent progress (MC@NLO) is limited to a handful of processes. More calculations are continually being added on a case-by-case basis.
- NLO predictions are available in far fewer cases than LO ones, e.g. no NLO QCD calculation of a $2 \to 4$ process.
- New analytic results for loop diagrams (via cutting rules and recursion) appear to be on the horizon, but so far have mostly been limited to theories with extra symmetry.

Small Expected Cross Section



General purpose NLO

- As a result of the complicated calculations required, there has been a proliferation of codes that compute NLO corrections.
- Some of the results in the literature cannot be reproduced by an interested physicist who wants to obtain predictions for a new set of experimental conditions.
- It would be useful to have a general purpose tool that streamlines the calculation of NLO corrections for today's colliders
  $\longrightarrow$ hadron colliders (the Tevatron and the LHC, soon)
  - $\star$ bring together accurate calculations of both signal and major background processes;
  - $\star$ provide a freely available tool that can be used by experimenters to compare with data. Calculations based on new values of physical parameters and selection cuts are easily performed;
  - $\star$ take advantage of modern techniques so that theoretical results can be recycled and new calculations are easy to add.

Theoretical status

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 2j$	$WW + 0j$	$WWW + \leq 3j$	$t\bar{t} + 0j$
$W + b\bar{b} + 0j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + 0j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 2j$	$ZZ + 0j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + 0j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + 0j$
$Z + c\bar{c} + 0j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + 0j$
$\gamma + \leq 1j$	$\gamma\gamma + \leq 1j$		$b\bar{b} + 0j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + 0j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + 0j$		
	$Z\gamma + 0j$		

Overview of MCFM

Overview

- Downloadable general purpose NLO code, “MCFM” JC and R.K. Ellis
(+F. Tramontano, +F. Maltoni, S. Willenbrock)

$p\bar{p} \to W^{\pm}/Z$	$p\bar{p} \to W^{+} + W^{-}$
$p\bar{p} \to W^{\pm} + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^{\pm} + \gamma$	$p\bar{p} \to W^{\pm}/Z + H$
$p\bar{p} \to W^{\pm} + g^{\star}\ (\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^{\pm}/Z +$ 1 jet	$p\bar{p} \to W^{\pm}/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	$p\bar{p} \to t + q$
$p\bar{p} \to H + b$	$p\bar{p} \to Z + b$
$p\bar{p} \to W + t$	

- NLO knowledge can be used in various ways.
  - ⋆ production of pairs of W’s and Z’s: the structure of the weak interaction at high energy
  - ⋆ $W/Z+$jets: testing QCD and sources of background events
  - ⋆ $H+2$ jets: an important discovery mode at the LHC

Comparison with other approaches

- There are generic routines for handling common tasks, so that implementing new processes is “painless”
- Emphasis has been on bringing together calculations of signals and backgrounds for particularly challenging searches, so that NLO effects may be more easily studied with just one code
- Where possible, appropriate decays of vector bosons are included and all possible spin correlations are retained for a better assessment of the effect of experimental cuts
  - $\ominus$ low particle multiplicity (no showering)
  - $\ominus$ no hadronization
  - $\ominus$ hard to model detector effects
  - $\oplus$ less sensitivity to μ
  - $\oplus$ rates are better normalized
  - $\oplus$ fully differential distributions

MCFM basics

- Written in Fortran 77, available at `http://mcfm.fnal.gov`.
- Operation of the program is mostly controlled by two files: `mdata.f` and `input.DAT`.
- The file `mdata.f` contains information on particle masses and couplings, for example:

```
data ewscheme  / -1                 /   ! Chooses EW scheme
data Gf_inp    / 1.16639d-5         /   ! G_F
data aemmz_inp / 7.7585538055706d-03 /  ! alpha_EM(m_Z)=1/128.89
data xw_inp    / 0.2312d0           /   ! sin^2(theta_W)
data wmass_inp / 80.419d0           /   ! W mass
data zmass_inp / 91.188d0           /   ! Z mass
```

- Most options for running the program are specified in `input.DAT`, with reference to the accompanying file `process.DAT`.
- The simplest output from the program is in the form of histograms (a standard set, but may be customized $\longrightarrow$ `nplotter.f`).

process.DAT

```
'4.2'          [file version number]
1  '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4))'
6  '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4))'
1000 'nul'
11 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4))+f(p5)'
12 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4))+gamma(p5)'
13 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4))+c~(p5)'
14 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4))+c~(p5) [massless]'
16 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4))+f(p5)'
17 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4))+gamma(p5)'
18 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4))+c(p5)'
19 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4))+c(p5) [massless]'
1000 'nul'
20 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4)) +b(p5)+b~(p6) [massive]'
21 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4)) +b(p5)+b~(p6)'
22 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4)) +f(p5)+f(p6)'
23 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4)) +f(p5)+f(p6)+f(p7)'
24 '  f(p1)+f(p2) --> W^+(-->nu(p3)+e^+(p4)) +b(p5)+b~(p6)+f(p7)'
25 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4)) +b(p5)+b~(p6) [massive]'
26 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4)) +b(p5)+b~(p6)'
27 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4)) +f(p5)+f(p6)'
28 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4)) +f(p5)+f(p6)+f(p7)'
29 '  f(p1)+f(p2) --> W^-(-->e^-(p3)+nu~(p4)) +b(p5)+b~(p6)+f(p7)'
1000 'nul'
31 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))'
32 '  f(p1)+f(p2) --> Z^0(-->3*(nu(p3)+nu~(p4)))'
33 '  f(p1)+f(p2) --> Z^0(-->b(p3)+b~(p4))'
1000 'nul'
41 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+f(p5)'
42 '  f(p1)+f(p2) --> Z_0(-->3*(nu(p3)+nu~(p4)))-[sum over 3 nu]+f(p5)'
43 '  f(p1)+f(p2) --> Z^0(-->b(p3)+b~(p4))+f(p5)'
1000 'nul'
44 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+f(p5)+f(p6)'
45 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+f(p5)+f(p6)+f(p7)'
1000 'nul'
48 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+gamma(p5)'
49 '  f(p1)+f(p2) --> Z^0(-->3*(nu(p3)+nu~(p4)))-[sum over 3 nu]+gamma(p5)'
1000 'nul'
50 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+b~(p5)+b(p6) [massive]'
51 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+b(p5)+b~(p6)'
52 '  f(p1)+f(p2) --> Z_0(-->3*(nu(p3)+nu~(p4)))+b(p5)+b~(p6)'
53 '  f(p1)+f(p2) --> Z^0(-->b(p3)+b~(p4))+b(p5)+b~(p6)'
56 '  f(p1)+f(p2) --> Z^0(-->e^-(p3)+e^+(p4))+b(p5)+b~(p6)+f(p7)'
```

- Each line corresponds to a process that can be calculated, mostly at next-to-leading order.
- $f(p_i)$ means a generic parton/jet
- The processes include the decays of the W, Z and top quark, including spin correlations. Cuts can be applied to all particles.
- The particles are numbered by p_i, which is used in the output of the program to label the histograms

`input.DAT` : *basic set-up*

```
 '4.2'           [file version number]

[Flags to specify the mode in which MCFM is run]
 .false.         [evtgen]
 .false.         [creatent]
 .false.         [skipnt]
 .false.         [dswhisto]

[General options to specify the process and execution]
1                [nproc]
'tota'           [part 'lord','real' or 'virt','tota']
 'demo'          ['runstring']
14000d0          [sqrts in GeV]
+1               [ih1 =1 for proton and -1 for antiproton]
+1               [ih2 =1 for proton and -1 for antiproton]
 120d0           [hmass]
80d0             [scale:QCD scale choice]
80d0             [facscale:QCD fac_scale choice]
.false.          [dynamicscale]
 .false.         [zerowidth]
 .false.         [removebr]
 10              [itmx1, number of iterations for pre-conditioning]
 50000           [ncall1]
 10              [itmx2, number of iterations for final run]
 50000           [ncall2]
 1089            [ij]
 .false.         [dryrun]
 .false.         [Qflag]
 .true.          [Gflag]

[Pdf selection]
 'cteq6_m'       [pdlabel]
 4               [NGROUP, see PDFLIB]
 46              [NSET - see PDFLIB]
 cteq61.LHgrid   [LHAPDF group]
 -1              [LHAPDF set]
```

- Specify the process to study with the integer `nproc`.
- Set the order of the calculation: lowest order (`lord`), next-to-leading order real diagrams (`real`), virtual diagrams (`virt`) or the total NLO result (`tota`).
- Choose the collider energy (`sqrts`) and beam composition (`ih1,ih2`).
- Enter the values of the renormalization and factorization scales (`scale` and `facscale`).
- For some processes, choosing scales on an event-by-event basis is also possible (`dynamicscale`).

`input.DAT` : *integration parameters*

```
'4.2'           [file version number]

[Flags to specify the mode in which MCFM is run]
 .false.        [evtgen]
 .false.        [creatent]
 .false.        [skipnt]
 .false.        [dswhisto]

[General options to specify the process and execution]
 1              [nproc]
 'tota'         [part 'lord','real' or 'virt','tota']
 'demo'         ['runstring']
 14000d0        [sqrts in GeV]
 +1             [ih1 =1 for proton and -1 for antiproton]
 +1             [ih2 =1 for proton and -1 for antiproton]
 120d0          [hmass]
 80d0           [scale:QCD scale choice]
 80d0           [facscale:QCD fac_scale choice]
 .false.        [dynamicscale]
.false.         [zerowidth]
 .false.        [removebr]
10              [itmx1, number of iterations for pre-conditioning]
50000           [ncall1]
10              [itmx2, number of iterations for final run]
50000           [ncall2]
1089            [ij]
 .false.        [dryrun]
 .false.        [Qflag]
 .true.         [Gflag]

[Pdf selection]
 'cteq6_m'      [pdlabel]
 4              [NGROUP, see PDFLIB]
 46             [NSET - see PDFLIB]
 cteq61.LHgrid  [LHAPDF group]
 -1             [LHAPDF set]
```

- Choose the description of resonances in the calculation (`zerowidth`): masses generated exactly at the peak (`true`) or off-shell (`false`). Important for $Z/\gamma^\star$.
- Choose the number of integration sweeps (`itmx1`) and points (`ncall1`) used in the warm-up stage of the calculation. `ncall1` should be increased when studying processes involving more particles.
- `itmx2` and `ncall2` are the values used when calculating all results.
- To produce distinct runs with otherwise-identical inputs, modify the random number seed `ij`.

`input.DAT` : *PDF specification*

```
 '4.2'           [file version number]

[Flags to specify the mode in which MCFM is run]
 .false.         [evtgen]
 .false.         [creatent]
 .false.         [skipnt]
 .false.         [dswhisto]

[General options to specify the process and execution]
 1               [nproc]
 'tota'          [part 'lord','real' or 'virt','tota']
 'demo'          ['runstring']
 14000d0         [sqrts in GeV]
 +1              [ih1 =1 for proton and -1 for antiproton]
 +1              [ih2 =1 for proton and -1 for antiproton]
 120d0           [hmass]
 80d0            [scale:QCD scale choice]
 80d0            [facscale:QCD fac_scale choice]
 .false.         [dynamicscale]
 .false.         [zerowidth]
 .false.         [removebr]
 10              [itmx1, number of iterations for pre-conditioning]
 50000           [ncall1]
 10              [itmx2, number of iterations for final run]
 50000           [ncall2]
 1089            [ij]
 .false.         [dryrun]
 .false.         [Qflag]
 .true.          [Gflag]

[Pdf selection]
'cteq6_m'        [pdlabel]
4                [NGROUP, see PDFLIB]
46               [NSET - see PDFLIB]
cteq61.LHgrid    [LHAPDF group]
-1               [LHAPDF set]
```

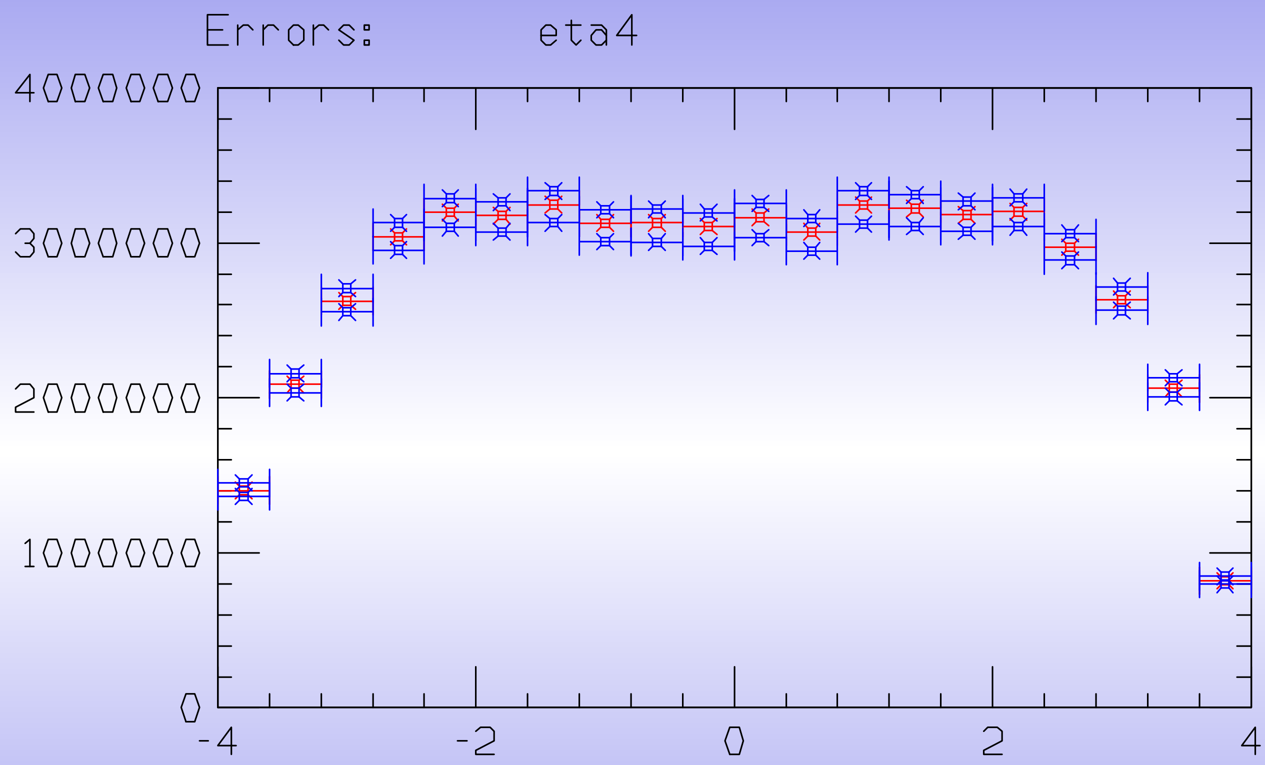
- The PDF set can be specified in one of 3 ways, depending on how the program is compiled
- The built-in implementations of popular MRS and CTEQ sets can be accessed via `pdlabel`.
- Access to PDFLIB is via the variables `NGROUP` and `NSET`.
- LHAPDF (successor to PDFLIB, see http://hepforge.cedar.ac.uk/lhapdf/) is the final option. Using this, the program can be used to evaluate PDF uncertainties (`LHAPDF set=-1`).

PDF demonstration

```
************ PDF error analysis ************
*                                          *
* PDF error set  0 ---> 11863519.187 fb    *
* PDF error set  1 ---> 11736647.263 fb    *
* PDF error set  2 ---> 11987706.935 fb    *
* PDF error set  3 ---> 11642296.578 fb    *
* PDF error set  4 ---> 12106702.170 fb    *
* PDF error set  5 ---> 11874355.602 fb    *
* PDF error set  6 ---> 11849124.661 fb    *
* PDF error set  7 ---> 11854123.307 fb    *
* PDF error set  8 ---> 11870788.530 fb    *
* PDF error set  9 ---> 11573575.545 fb    *
* PDF error set 10 ---> 12215308.143 fb    *
* PDF error set 11 ---> 12048942.634 fb    *
* PDF error set 12 ---> 11691755.691 fb    *
* PDF error set 13 ---> 11874942.354 fb    *
* PDF error set 14 ---> 11853027.865 fb    *
* PDF error set 15 ---> 11758576.633 fb    *
* PDF error set 16 ---> 11913098.358 fb    *
* PDF error set 17 ---> 11779363.844 fb    *
* PDF error set 18 ---> 11901319.122 fb    *
* PDF error set 19 ---> 12010652.500 fb    *
* PDF error set 20 ---> 11740933.791 fb    *
* PDF error set 21 ---> 11985450.352 fb    *
* PDF error set 22 ---> 11890845.603 fb    *
* PDF error set 23 ---> 11920163.560 fb    *
* PDF error set 24 ---> 11957587.988 fb    *
* PDF error set 25 ---> 11866956.994 fb    *
* PDF error set 26 ---> 11984564.841 fb    *
* PDF error set 27 ---> 11750019.234 fb    *
* PDF error set 28 ---> 11721240.685 fb    *
* PDF error set 29 ---> 11987664.142 fb    *
* PDF error set 30 ---> 11484760.388 fb    *
* PDF error set 31 ---> 11659901.056 fb    *
* PDF error set 32 ---> 11957864.136 fb    *
* PDF error set 33 ---> 11962671.598 fb    *
* PDF error set 34 ---> 11964869.177 fb    *
* PDF error set 35 ---> 11748873.948 fb    *
* PDF error set 36 ---> 11704653.918 fb    *
* PDF error set 37 ---> 11693637.274 fb    *
* PDF error set 38 ---> 11745558.021 fb    *
* PDF error set 39 ---> 11803672.011 fb    *
* PDF error set 40 ---> 11795692.786 fb    *
*                                          *
* --------------- SUMMARY ---------------- *
*                                          *
*      Minimum value  11484760.388 fb      *
*      Central value  11863519.187 fb      *
*      Maximum value  12215308.143 fb      *
*                                          *
*   Err estimate +/-    570618.935 fb      *
*      +ve direction    587609.633 fb      *
*      -ve direction    720774.743 fb      *
********************************************
```

- Sample output from a PDF uncertainty run. The program has used the CTEQ6 uncertainty sets (1 central + 40 others) and calculates W^+ production at NLO at the LHC.
- Rather than running the program 41 separate times, the cross section is evaluated for all PDF uncertainty sets at once. This is typically about 3–4 times slower than a normal run.
- The cross section is reported for each PDF set, then summarized at the end. The uncertainties are calculated according to the method laid out in `hep-ph/0101032`.
- In this case the uncertainty in the cross section due to the PDF is about 5%. This is a fairly typical result.

PDF uncertainties

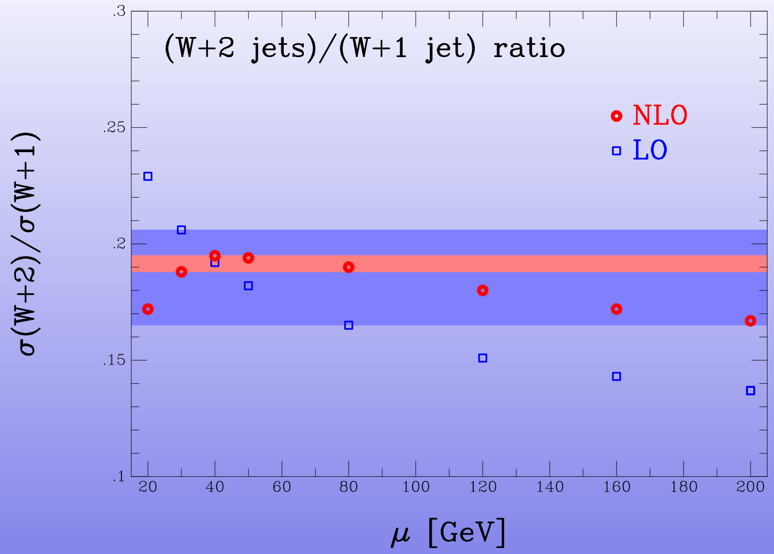


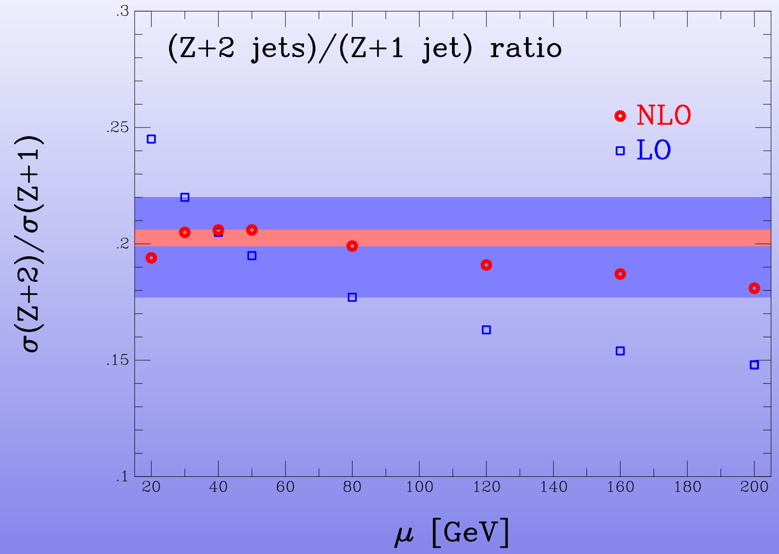
- Lepton pseudo-rapidity distribution at NLO.
- Central values are in red, extremal PDF values in blue. Note that in each bin, the PDF uncertainty set providing the extreme value may be different.

W/Z+jets cross-sections

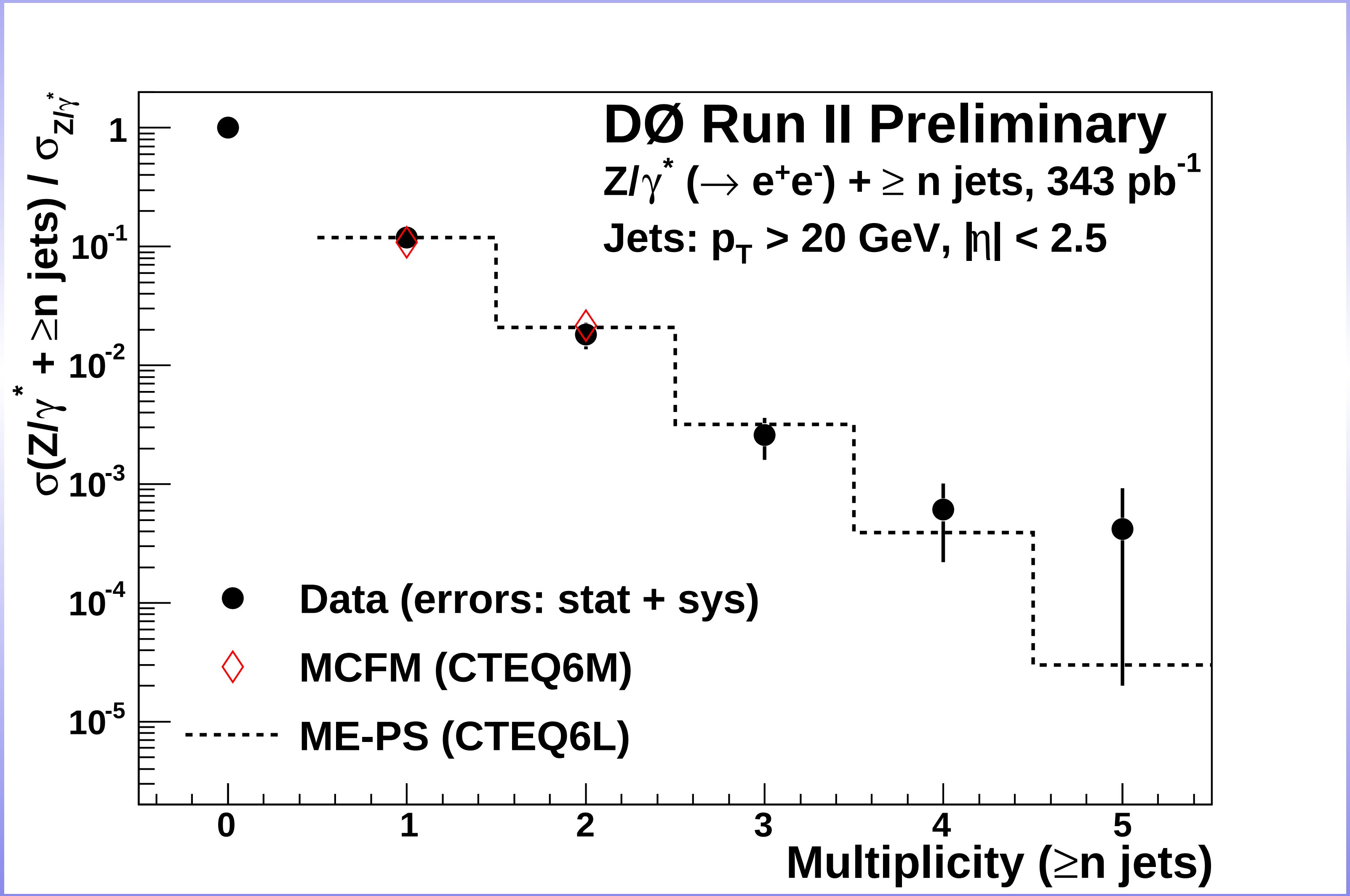
Rates at the Tevatron

- The $W/Z+2$ jet NLO calculation is the most complicated (time-consuming) process currently implemented. This is due to both the lengthy virtual matrix elements (vector boson $+4$ partons) and the complicated structure of phase space.
- The usual features such as reduced scale dependence are observed, e.g. the theoretical prediction for the number of events containing 2 jets divided by the number with only 1 is improved.



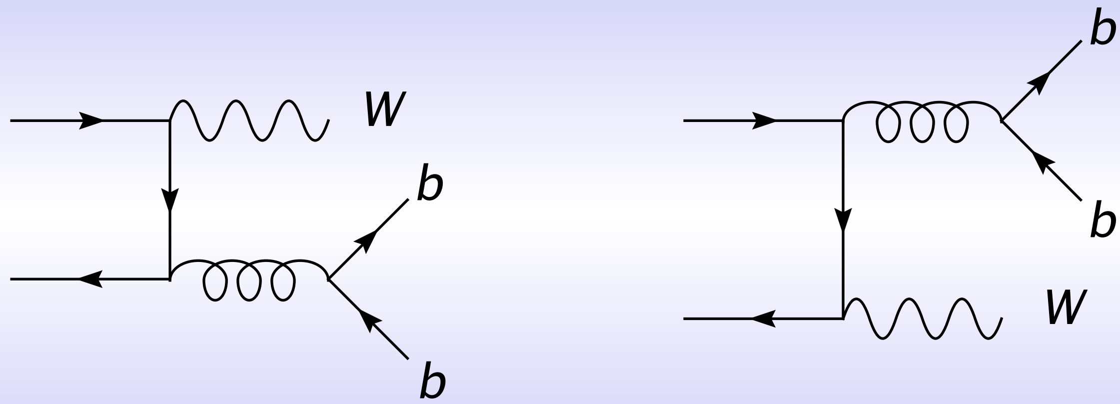


Preliminary data



Vector boson + heavy flavour

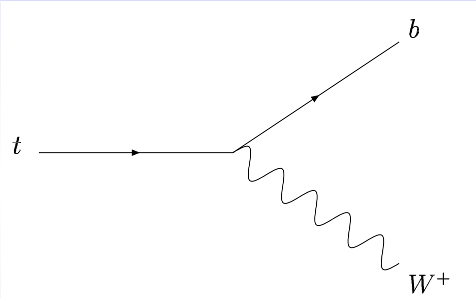
- In lowest order bottom quark pairs are produced in association with W's by gluon splitting alone:



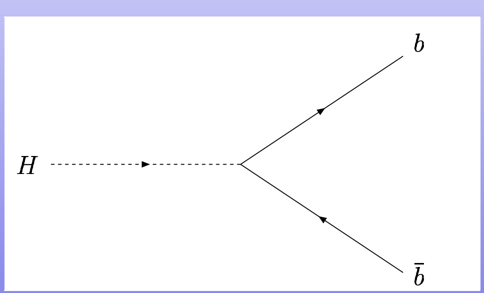
- Beyond LO, the b-quark is treated as a massless particle in MCFM
  - ⋆ a finite cross-section requires a cut on the b-quark p_T
  - ⋆ this means that this calculation is not suitable for estimating the rate with only a single b tag

Heavy flavour as a background

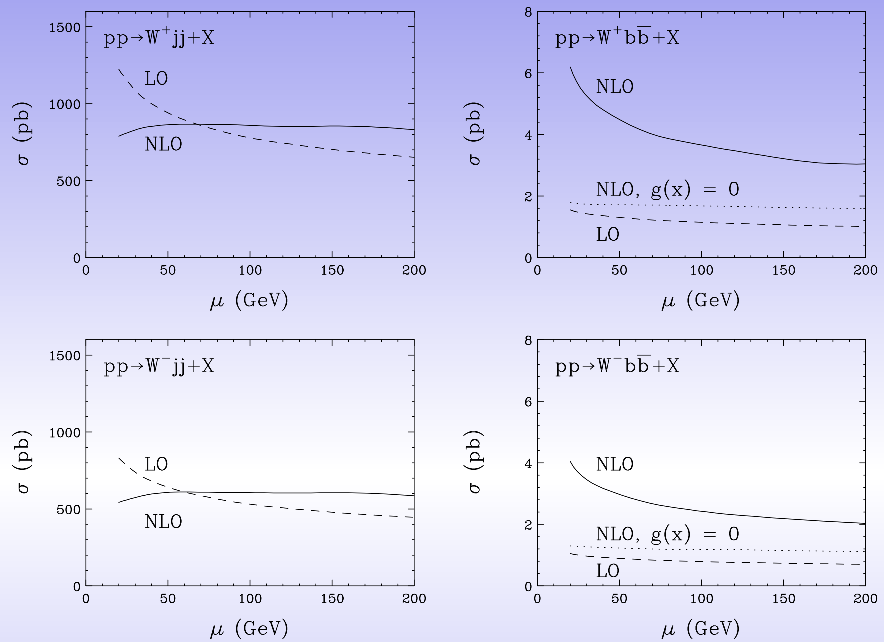
- Events containing jets that are heavy-quark tagged are important for understanding both old and new physics:
  - ⋆ Top decays $t \to W + b$



  - ⋆ Much new physics couples preferentially to massive quarks, for instance a light Higgs with $m_H < 140$ GeV decaying to $b\bar{b}$

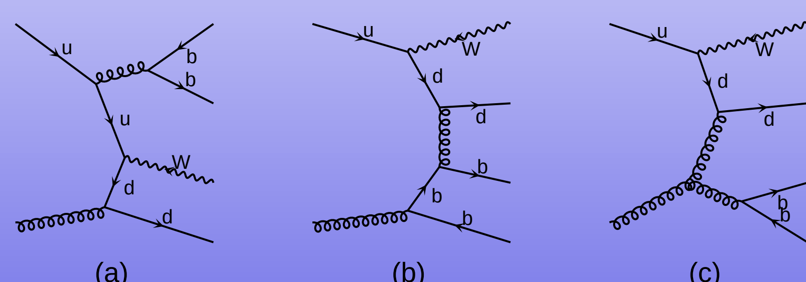


Jets and heavy flavour at the LHC



- The large gluonic contribution appearing in $Wb\bar{b}$ for the first time at NLO results in a huge correction and poor scale dependence.

Diagrams by MadGraph

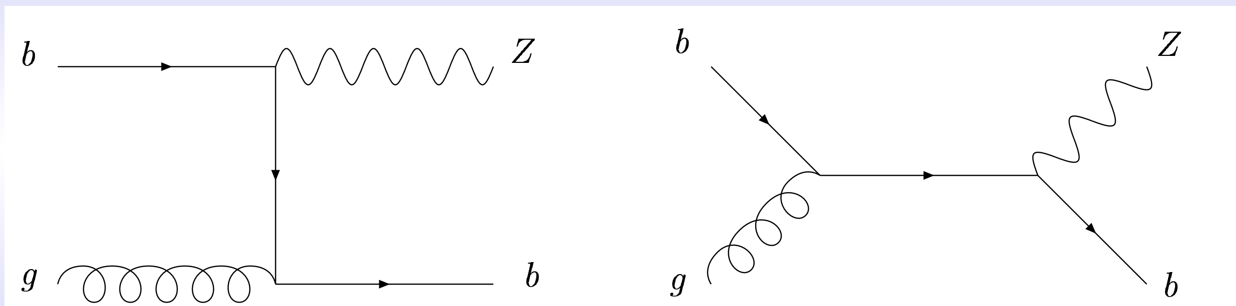


Single-tagged heavy flavour

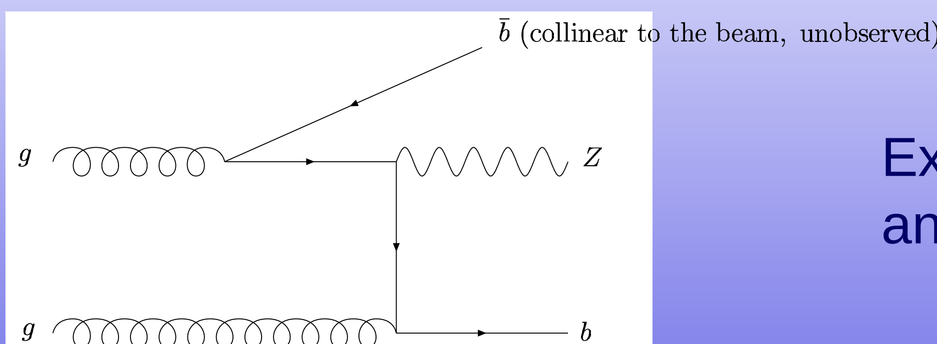
JC, Ellis, Maltoni, Willenbrock

Heavy flavour fraction revisited

- Often the presence of two b-quarks in the final state is actually only inferred from a single b-tag
- In this case, there is another way of computing the theoretical cross-section. For instance, in the case of $Z+$ heavy flavour:



- Requires knowledge of b-quark pdf's, but compare to:



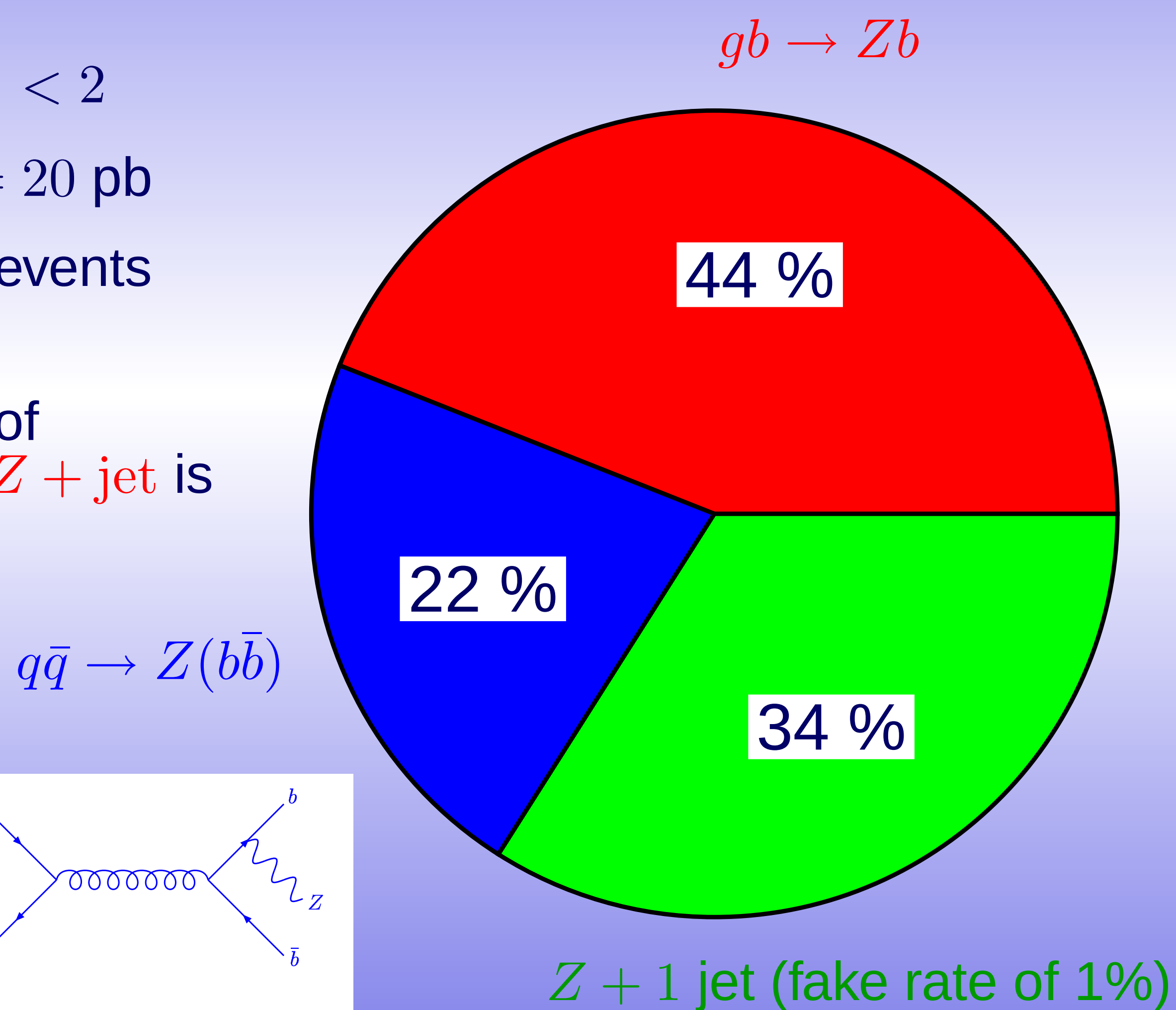
Expansion in $\alpha_s \ln(M_Z/m_b)$
and NLO calculation difficult

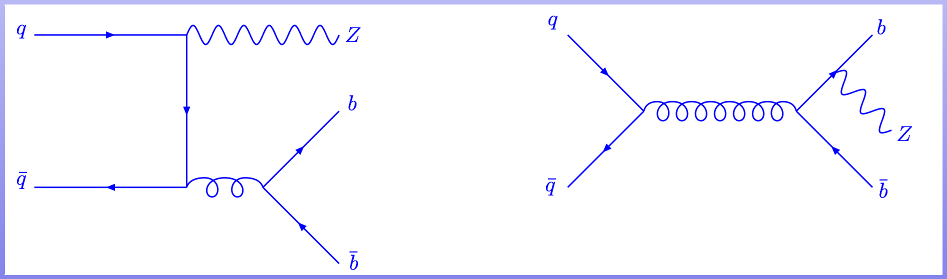
$Z + b$ *at NLO - Run II*

JC, K. Ellis, F. Maltoni and S. Willenbrock, hep-ph/0312024

- $p_T^{\rm jet} > 15$ GeV, $|\eta^{\rm jet}| < 2$
- $\sigma(Z + \text{ one } b \text{ tag}) = 20$ pb
- Fakes from $Z+$ jet events are significant
- Prediction for ratio of $Z + b$ to untagged $Z + \text{jet}$ is

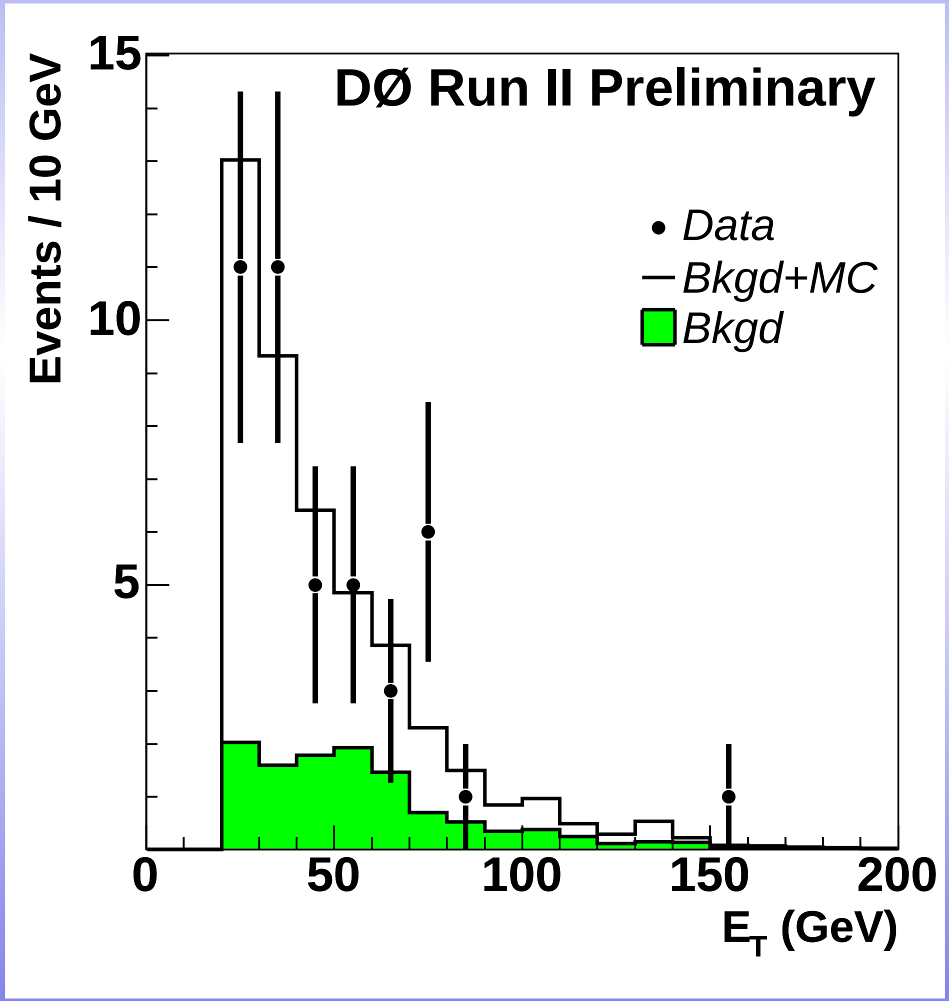
  0.02 ± 0.004





Experimental result

- Based on $189\ \mathrm{pb}^{-1}$ of data from Run II



Ratio of cross-sections:

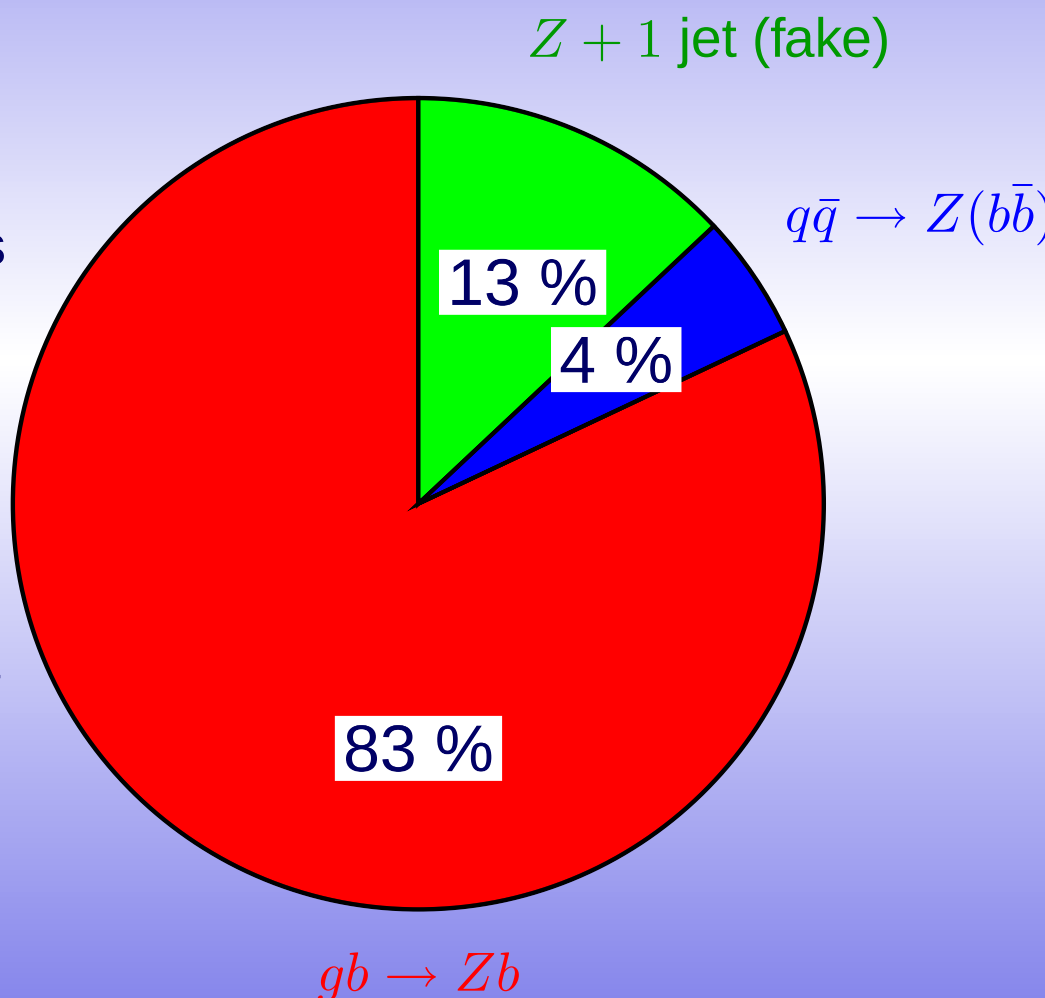
$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.007$$

compatible with the NLO prediction from MCFM

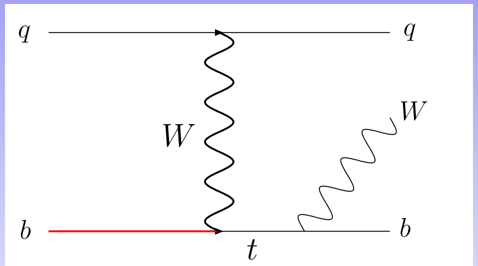
More data and detailed analysis is on the way (CDF too) .

LHC expectations

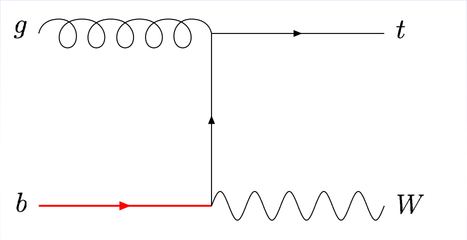
- $p_T^{\mathrm{jet}} > 15$ GeV, $|\eta^{\mathrm{jet}}| < 2.5$
- $\sigma(Z + \text{ one } b \text{ tag}) = 1$ nb
- Fakes from $Z+$ jet events are much less significant and $q\bar{q}$ contribution is tiny
- This should allow a fairly clean measurement of heavy quark PDF's (currently, only derived perturbatively)



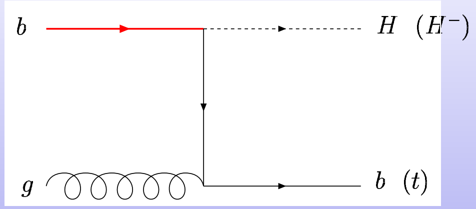
b-PDF uses



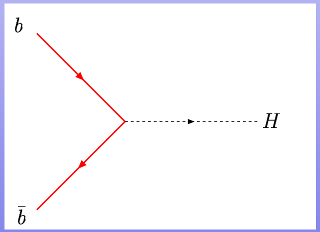
single-top $qb \to qWb$



single-top $gb \to tW$



(charged) Higgs+b

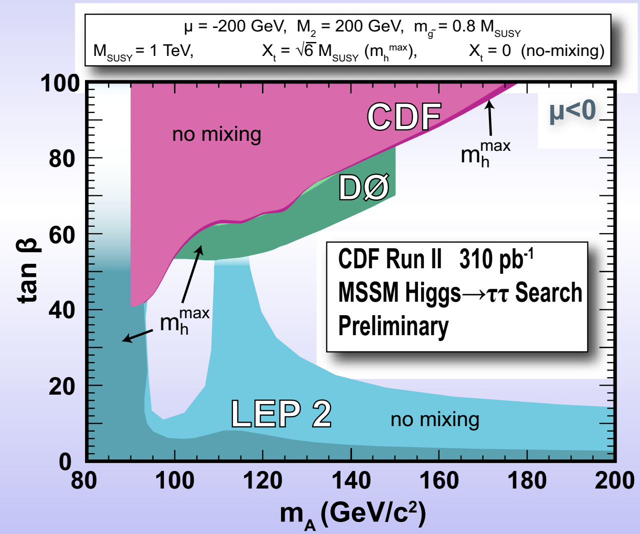


inclusive Higgs

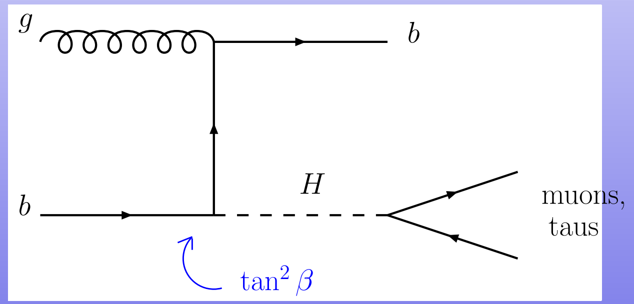
Example: H+b production

- Various supersymmetric extensions to the Standard Model utilize more than one Higgs doublet. In these models, the Yukawa coupling of some of the Higgs bosons to bottom quarks can be enhanced by the ratio of vacuum expectation values, $\tan\beta$.

- Allowed values of $\tan\beta$ depend on the exact details of the proposed model. However, it has been constrained both at LEP and the Tevatron and its value can be large.



- Discover such a Higgs at the LHC via its production in association with a single high p_T bottom quark.



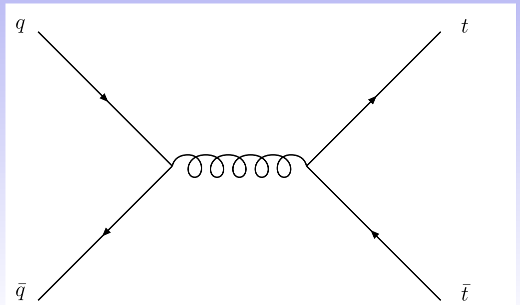
- Test experimental procedure and systematics for this search by first re-discovering the Z.

Single top production and decay

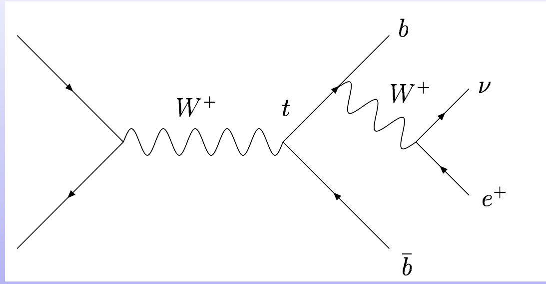
JC, Ellis, Tramontano

Producing the top quark

- The top quark was discovered in Run I of the Tevatron by producing it in pairs:

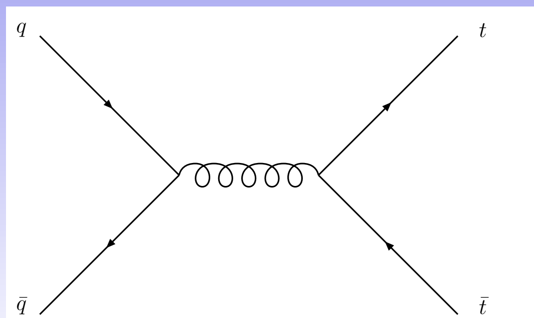


- However, it should also be possible to produce it singly in Run II, for example:

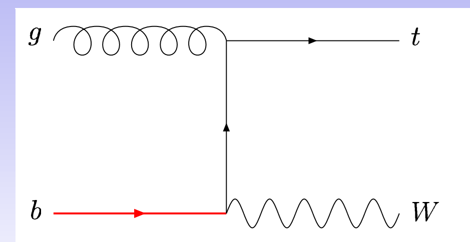


- This is especially interesting since it would yield information about the weak interaction of top quarks (V_{tb}).

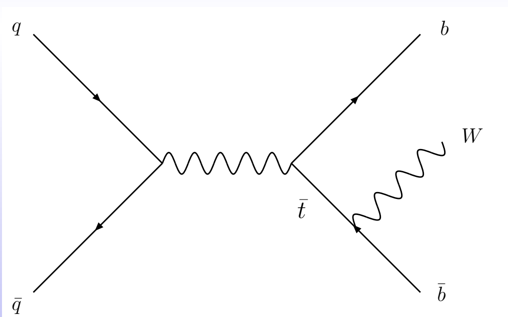
Top production rates



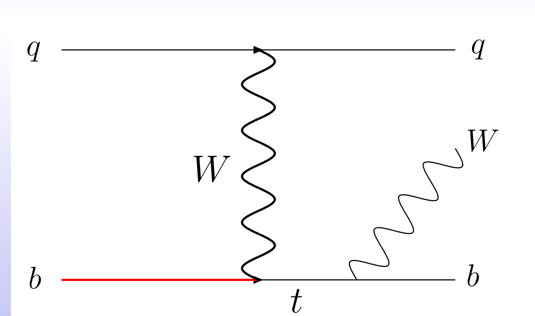
6 pb
720 pb



0.14 pb
66 pb



0.8 pb
10 pb

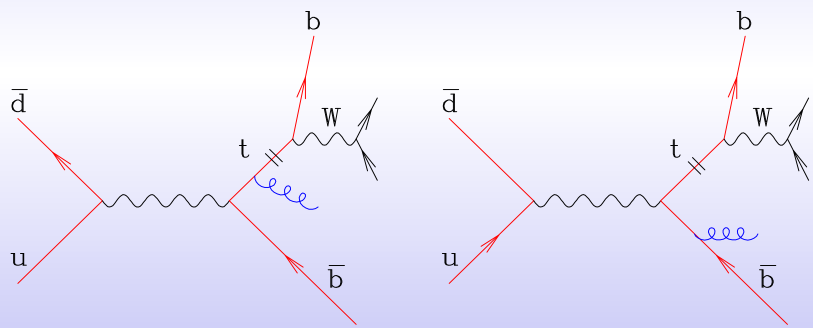


1.8 pb
240 pb

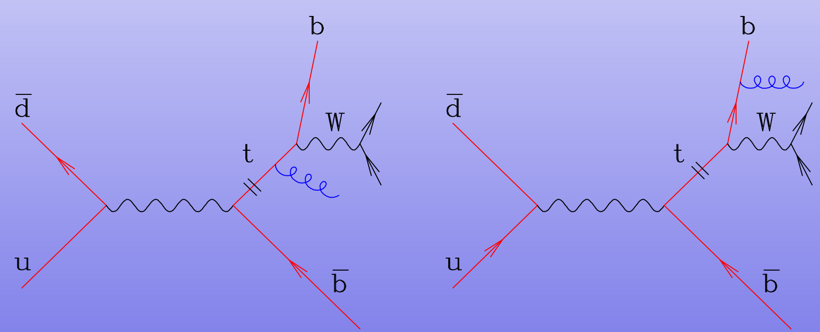
- All cross-sections are known to NLO (Tevatron / LHC)
- The total single top cross-section is smaller than the $t\bar{t}$ rate by about a factor of two, at both machines

Inclusion of decay

- Results had previously been presented without including the decay of the top quark. Without it, predictions for some quantities used in Tevatron search strategies are impossible
- Final state radiation that enters at next-to-leading order is possible in either the production or decay phase:

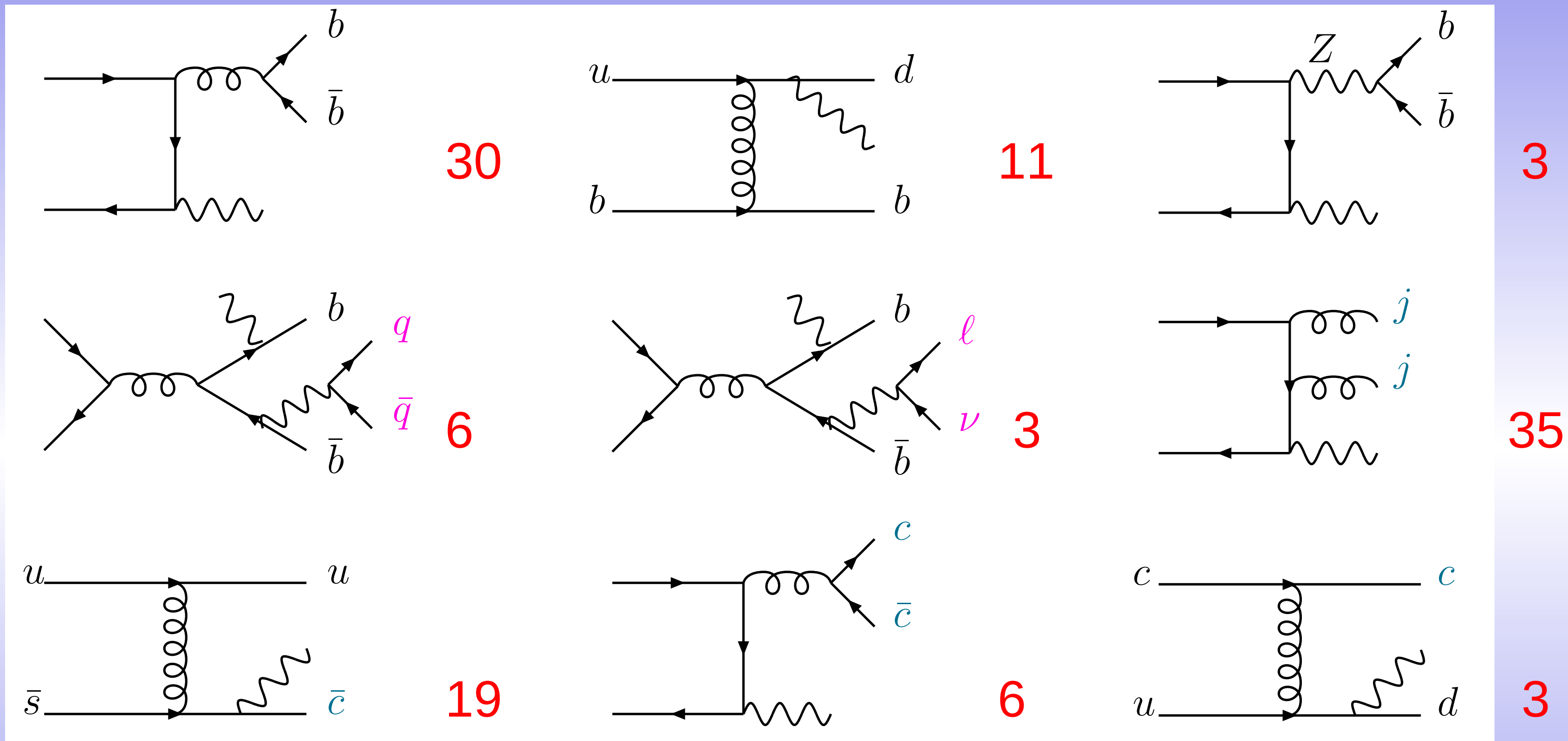


production



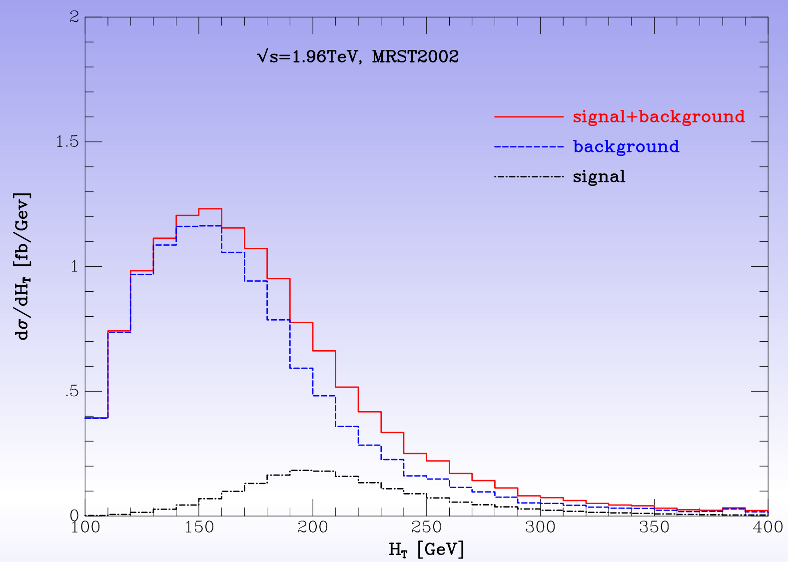
decay

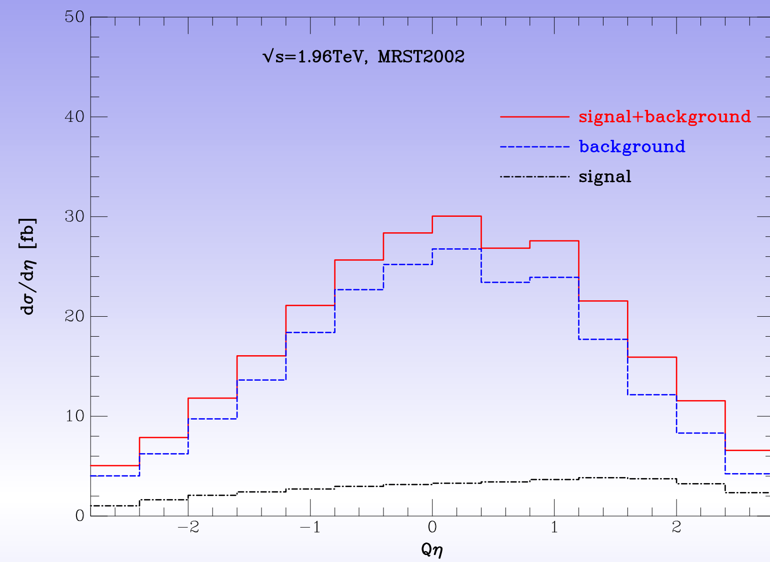
Backgrounds at the Tevatron



- Cross-sections in fb include nominal tagging efficiences and mis-tagging/fake rates. Calculated with MCFM, most at NLO
- Rates are 7 fb and 11 fb for s- and $t-$channel signal

Single top signal vs. backgrounds





- $H_T =$ scalar sum of jet, lepton and missing E_T
- $Q\eta$ is the product of the lepton charge and the rapidity of the untagged jet, useful for picking out the t-channel process
- Signal:Background (with our nominal efficiencies) is about $1:6$ – a very challenging measurement indeed. Production in this mode has not yet been observed at Fermilab.
- Knowing the characteristics of signal and background events at NLO should help. D0 estimate $7\,\mathrm{fb}^{-1}$ for a 5σ observation.

Shortcomings

The approach in MCFM involves a number of approximations:

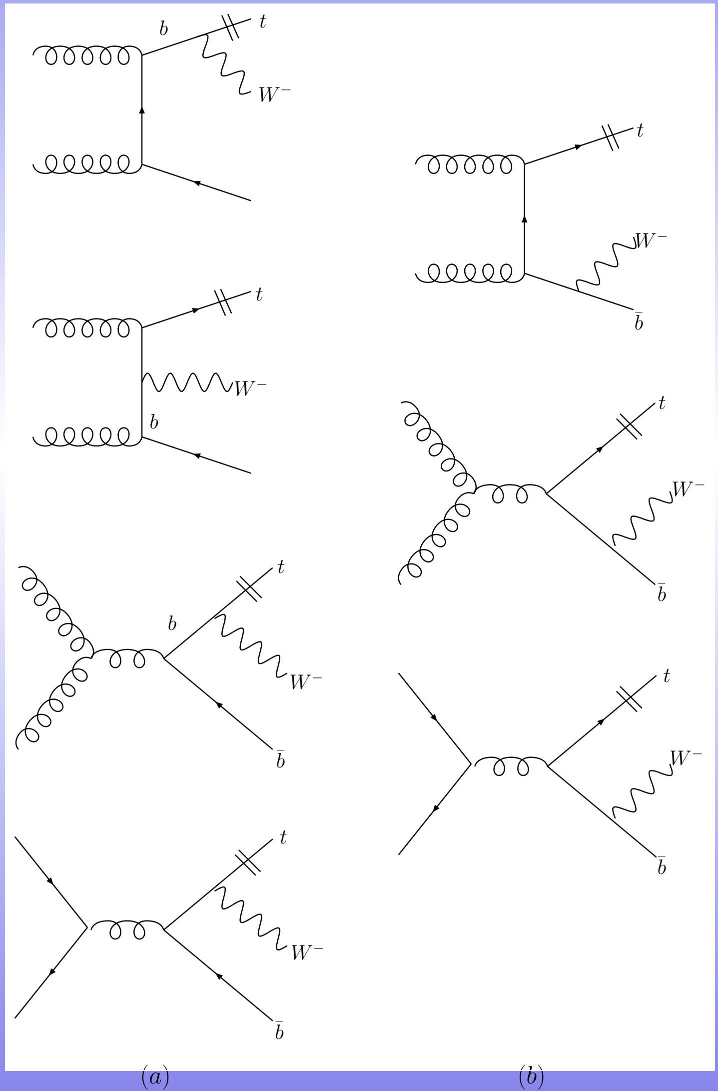
- The b-quark is massless
  LO calculation with $m_b = 4.75$ GeV $\longrightarrow < 1\%$ effect
- The top quark is put on its mass-shell
  LO calculation with a Breit-Wigner $\longrightarrow 1\%$ effect
- We neglect interference between radiation in production/decay
  qualitative argument for $\mathcal{O}(\alpha_s \Gamma_t / m_t) \sim$ less than a percent
- We assume p_T-independent heavy flavour tagging efficiencies, as well as stable b and c quarks
  easily addressed by a more detailed experimental analysis
  with the publicly-available code
- No showering or hadronization is performed
  no NLO/PS prediction yet available; however the large cone
  size $\Delta R = 1$ should help minimize these effects

Associated Wt production

JC, Tramontano

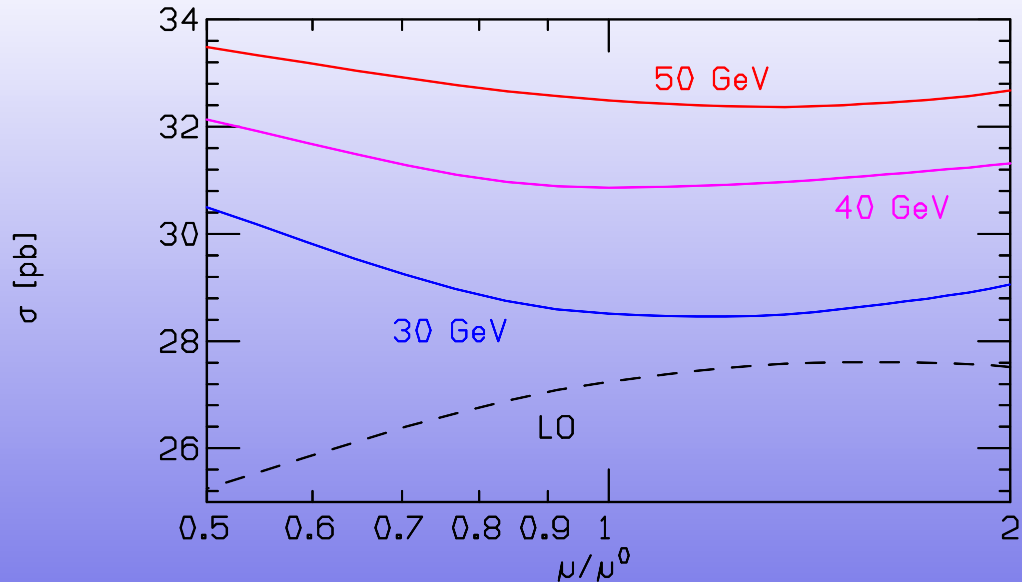
Resonant complications

- Most details of the calculation proceed as normal.
- NLO real radiation corrections contain the process $gg \to Wtb$. This final state is also obtained by producing two top quarks on shell.
- Including this contribution doesn't give a meaningful result.
- Previous attempts to remove it involve either subtracting the resonant contribution or applying an invariant mass cut.
- Neither of these is suitable for a MC approach including decays.



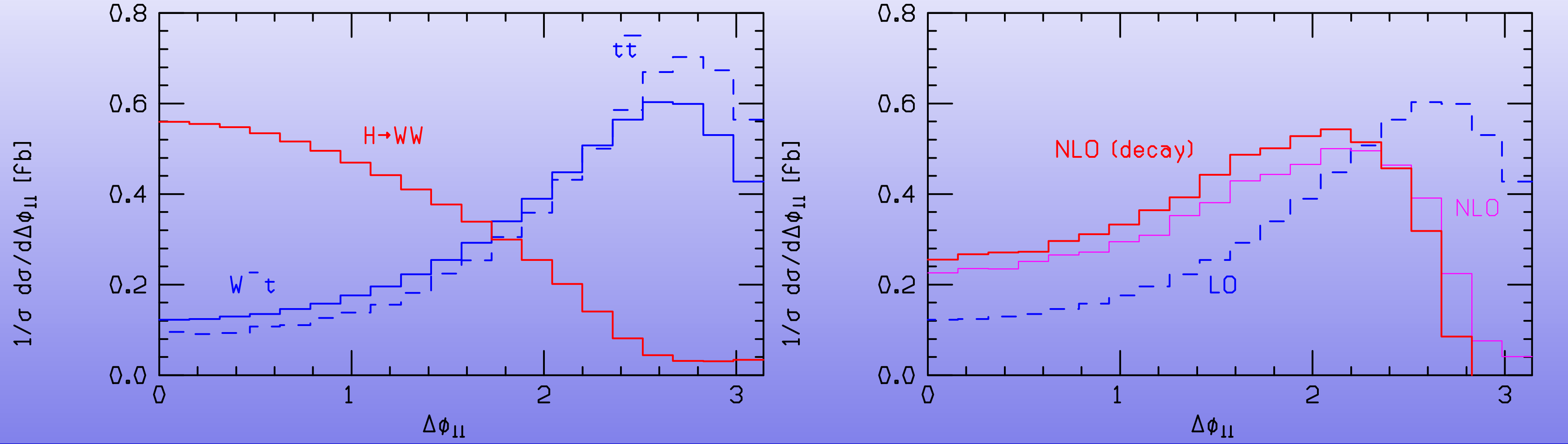
Solution

- The contribution from the troublesome diagrams when the b quark p_T is small is already accounted for by the b-quark PDF.
- When the b quark p_T is large, the event should be best described by resonant $t\bar{t}$ production anyway.
- Therefore, define the Wt process by demanding that no b quark be observed above a given value of $p_T = \mu_V$. Factorization and renormalization scales should also be chosen equal to μ_V.
- As a result, the NLO prediction depends on the value chosen for μ_V.
- Once accounted for in this way, the corrections are mild.



Application: $gg \to H \to WW^*$

- $155 < m_H < 180$ GeV, so W's decay to leptons. Signal is two leptons and missing E_T
- Main background is from continuum W pair production, via $q\bar{q}$ scattering and loop-induced gluon-gluon fusion
- Further backgrounds from events containing leptonically-decaying top quarks where the jets are not observed
- Enhance signal using strong cuts. The opening angle between the leptons in the transverse plane is a good discriminator.



Where now for NLO?

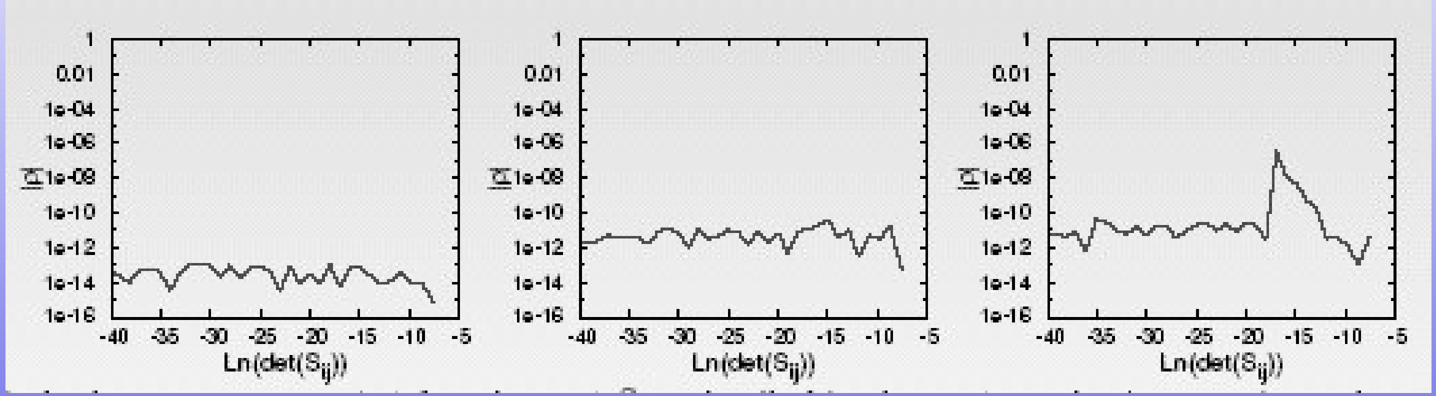
A new approach

- Current calculations are performed on a case-by-case basis and take many man-years.
- The real radiation corrections are essentially tree level evaluations together with well-understood rules for removing singular regions.
- The bottleneck is the calculation of the loop diagrams.
- In recent years a number of attempts have been made to perform these calculations numerically. These are complicated by the infrared and ultraviolet divergences that appear.
- By the time the LHC is taking data, can we expect the evolution of automated computer programs for the evaluation of NLO corrections, e.g. MadEvent $\longrightarrow$ MadLoop?

A recent attempt

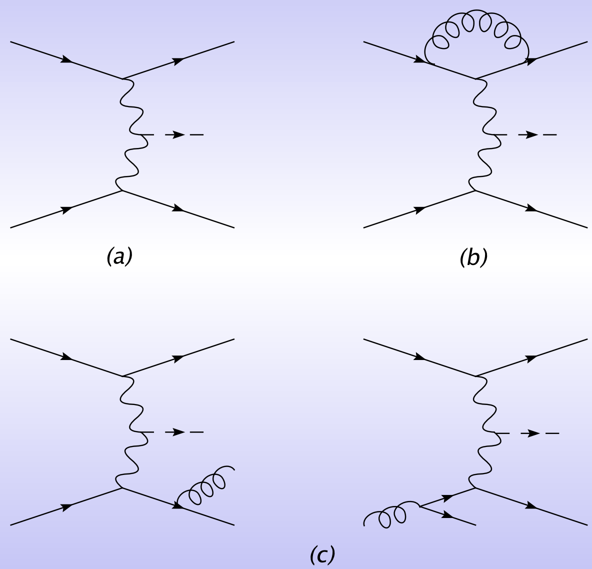
Ellis, Giele, Zanderighi

- Use a numerical implementation of recursion relations to reduce all integrals into a set of basis integrals that are known analytically
- The concept has been demonstrated by performing the calculation of the virtual contributions to $H + 2$ jet production. Three different partonic matrix elements:
  - $\star$ $H \to$ 4 quarks (analytic, numerical)
  - $\star$ $H \to$ 2 quarks, 2 gluons (numerical only)
  - $\star$ $H \to$ 4 gluons (numerical only)
- The calculation of the 4 quark contribution agrees to machine precision between the analytic and numerical evaluation



LHC application

- Can use the WBF $H + 2$ jet process to measure the coupling of the Higgs to W's and Z's. The NLO corrections to WBF are small and well-understood.



- The numerical virtual evaluation is the final piece necessary for assembling the full calculation of the QCD $H + 2$ jet corrections.
- This irreducible 'background' will be under much better theoretical control, allowing for a more accurate coupling determination.

Summary

- Events seen in collider physics experiments at Fermilab and CERN can (and will) be described very well with the theory of perturbative QCD.
- However, making an accurate assessment of particle rates and extracting detailed information from the data requires calculations that go beyond the simplest approximation.
- Next-to-leading order calculations are the first step towards precision. However, their difficulty means that there are many interesting analyses which are still not possible at this accuracy.
- This is highlighted at the LHC where, on average, many more particles are produced per collision.
- In parallel with the huge undertakings to further expand the “energy frontier”, theorists need to provide ever more generic and accurate predictions to keep pace.
- New avenues of research and better tools are inevitable.